MASSACHUSETTS INSTITUTE OF TECHNOLOGY
DEPARTMENT OF PHYSICS
CAMBRIDGE, MASSACHUSETTS 02139

Final Technical Report

R&T Number: 4128012-01

Contract/Grant Number: N00014-91-J-1587

Contract/Grant Title: "Mesoscopic Supercurrent Fluctuations in SNS Josephson Junctions"

Principal Investigator: Professor John M. Graybeal, MIT Physics (now at the University of Florida)

Mailing Address: MIT, 77 Massachusetts Avenue, 13-2077, Cambridge, MA 02139 (Present address: University of Florida, 215 Williamson Hall, P.O. Box 118440, Gainesville, FL 32611-8440)

Phone Number: (617) 253-6189 (Present phone: (904) 392-5711)

E-mail address: graybeal@noleak.mit.edu (Present e-mail: graybeal@phys.ufl.edu)

a. *Number of Papers Submitted to Refereed Journals but not yet Published:* 1, plus two manuscripts in progress

b. *Number of Papers published in Refereed Journals:* 3

c. *Number of Books or Chapters Submitted but not yet Published:* 0

d. *Number of Books or Chapters Published:* 0

e. *Number of Printed Technical Reports & Non-Refereed Papers:* 0

f. *Number of Patents Filed:* 0

g. *Number of Patents Granted:* 0

h. Number of Invited Presentations at Workshops or Prof. Society Meetings: 2

Aspen Winter Condensed Matter Physics Conference (Jan. 1993).

ISI Euroconference on Coherence and Phase Transitions in Superconductors and Mesoscopic Structures, Torino, Italy (Sept. 1993).

i. Number of Presentations at Workshops or Prof. Society Meetings: 5

j. Honors/Awards/Prizes for Contract/Grant Employees: 0

k. Total Number of Students and Postdocs Supported at least 25% this year on this contract/grant:

Grad students: 1

Grad Students Female: 0

Grad Students Minority: 0

Undergraduate students: 1

Undergraduate Female: 0

Undergraduate Minority: 1

Postdocs: 0

Postdocs Female: 0

Postdocs Minority: 0

List of Papers Published in Refereed Journals:

J.M. Graybeal, J. Luo and W.R. White, "Interlayer Vortex Coupling and the Hall Sign Reversal in MoGe/Ge Multilayers", *Phys. Rev. B* **49**, 12923 (1994).

D.G. Steel, W.R. White and J.M. Graybeal, "Direct Observation of Vortex Decoupling in Synthetic MoGe/Ge Multilayers", *Phys. Rev. Lett.* **71**, 161 (1993).

D.G. Steel and J.M. Graybeal, "Investigation of the ac Screening Response in the Mixed State of $Bi_2Sr_2CaCu_2O_8$ Single Crystals", *Phys. Rev. B Rapid. Comm.* **45**, 12643 (1992).

List of Papers Submitted to Refereed Journals but not yet Published:

D.G. Steel, W.R. White and J.M. Graybeal, "Direct Observation of Vortex Decoupling in Synthetic MoGe/Ge Multilayers", to appear in the Proceedings of the 20th International Conference on Low Temperature Physics (LT20), Eugene, Oregon 1993.

List of Manuscripts in Progress:

"Josephson currents in Nb-CuMn-Nb junctions: Measurement of the dephasing time in a spin glass", S.K. Anderson and J.M. Graybeal.

"Upper Bound on the Supercurrent Fluctuations in Mesoscopic SNS Josephson Junctions", S.K. Anderson and J.M. Graybeal.

Summary of Research Accomplishments

Direct measurement of the dephasing time in the spin glass Cu-Mn

Key achievements:

- First demonstration of using the temperature dependence of the supercurrent in an SNS Josephson junction to measure the dephasing time of a novel magnetic normal-state metal.
- Results for the dephasing time in CuMn are in agreement with a recent theoretical model for spin-flip scattering within the spin-glass state.

In examining the mesoscopic supercurrent fluctuations (i.e., the deviations from ensemble-averaged behavior) in SNS Josephson junctions, we fabricated numerous junctions which contained the metallic spin glass Cu-Mn ($Cu_{.9975}Mn_{.0025}$) as the normal metal. In measuring the current-voltage behavior of these junctions at low temperatures, we discovered that their ensemble *averaged* behavior was of considerable interest as well. In addition to inferring the unusual low-temperature behavior of the electronic dephasing length of CuMn from the superconducting properties of these junctions, we believe that we have discovered a more general technique for measuring the electronic scattering times in novel magnetic metals at low temperatures. It is important to note that the usual technique for determining the electronic scattering lengths, i.e, the magnetoresistance, often cannot be used for unusual magnetic materials. In a spin glass, for example, the applied field not only dephases the electrons (as assumed for the weak localization contribution to the magnetoresistance) but also strongly modifies the ground state properties. This latter effect, which does not exist in ordinary non-magnetic metals, leads to a significant contribution to the magnetoresistance which overwhelms (by orders of magnitude) the contribution due to weak localization.

For our chosen composition Cu-Mn has a bulk spin glass temperature of approximately 3.5K, while thin films have a reduced temperature of about 2.5K. All junctions were fabricated using direct electron-beam lithography, with junction parameters as follows: junction width 2.1μm, junction cross-sectional area $A=1.05\times10^{-9}$ cm^2, and junction lengths L_x varying from 800Å to 2000Å. Out of

several dozen working devices, we chose to most closely examine the behavior of three representative junctions with lengths L_x=1000Å, 1400Å, and 1700Å. Their current-voltage characteristics were measured from above $T_c \approx 7.5K$ to roughly 0.3K.

The general expression for the supercurrent in a "conventional" SNS junction (with junction length $L_x \gg \ell$, the electronic mean free path in the normal metal) is:

$$I_c(T) = I_o \left(1-(T/T_c)^4\right) \exp\left(-L_x/\xi_n(T)\right) ,$$

where: $$I_o = \frac{\Delta_o A}{e \rho L_x} \quad \text{and}$$

$$\xi_n(T) = \frac{\hbar D}{kT} .$$

Here Δ_o is the zero-temperature superconducting gap of the Nb counterelectrodes, ρ is the resistivity of the normal metal, and e is the electronic charge, $\xi_n(T)$ is the temperature dependent normal-metal coherence length, and D is the electronic diffusion constant.

In order to test the validity of the above expression for conventional normal metals, we separately made a series of Nb/Cu/Nb junctions using identical deposition and fabrication techniques. These critical current of these Nb/Cu/Nb junctions were found to provide excellent qualitative and quantitative agreement with the predicted dependences as functions of temperature and the device length. Note that the device geometry was independently measured via electron microscopy, and thus was not a variable in the fits. This high level of agreement provided an important proof upon our sample fabrication technique as well as our experimental methods. Thus, our spin glass junctions only differ from such Nb/Cu/Nb junctions by the mere addition of 0.25% Mn to the Cu layer.

For our CuMn junctions, ρ=3.5 $\mu\Omega$-cm, which in turn predicts a prefactor in the above expression for the supercurrent I_o of order several tens of milliamps (mA). As this is approximately two orders of magnitude larger than the observed $I_c(0)$, it implies a short normal-metal coherence length, i.e., $\xi_n \ll L_x$. However, the CuMn data could not be fit by the traditional $T^{-1/2}$ dependence for $\xi_n(T)$, with dramatic deviations from the predicted behavior for temperatures below $T \lesssim 0.8T_c$. Furthermore, the magnitude of the suppression of $I_c(T)$ implied values for ξ_n which were far too short in light of the value for the electronic diffusion constant D for our CuMn. Viewed together with our previous excellent agreement for the Nb/Cu/Nb

junctions, it was clear that additional scattering processes were responsible for the suppression of he critical current and its anomalous temperature dependence.

We point out that previous measurements of Pb-CuMn-Pb junctions were found in the literature.[1] In presenting their more limited data, these workers noted that the temperature dependence could be empirically fit to the functional form $I_c(T) = \alpha \exp(-L_x T^{1.5}/\beta)$. Here α and β are independent of temperature. However, they do not present and we no of no physical justification for this functional form.

An important observation is the fact that the normal metal coherence length can be written in terms of scattering time τ_i for the various independent scattering channels as:

$$\frac{1}{\xi_n^2(T)} = \frac{1}{D} \sum_i \frac{1}{\tau_i} = \sum_i \frac{1}{\xi_n^2} .$$

Note the conventional case listed above corresponds only to the single contribution of $\tau=\hbar/kT$. It is this expression which points to the viability of using the critical current of an SNS junction to measure the scattering times of the N metal.

In the presence of local magnetic moments, an additional contribution to the electronic dephasing rate is expected to come from spin-flip scattering, whereby the electron flips its spin s_z while changing the orientation of the spin S_z on the magnetic ion. Since the total change in spin must be zero, $\Delta s_z + \Delta S_z = 0$, with $\Delta s_z = \pm 1 = -\Delta S_z$. For non-ordered or "free" magnetic ions, one expects

$$\frac{1}{\tau_s} = \frac{\hbar}{cJ} .$$

where c is the concentration of magnetic ions and J is the RKKY exchange energy. For Mn ions in Cu, the measured value for J is 0.33 eV. However, at sufficiently low temperatures where the Mn ions can order, the z-component of their spins should take on their maximum value $S_z=S$ due to the presence of the nonzero local field. Then only those electrons which are *anti-aligned* with the Mn ion can spin-flip scatter. Thus in the frozen state on expects

$$\frac{1}{\tau_s} = \frac{2\hbar}{cJ}, \text{ hence}$$

$$\frac{1}{\xi_s^2} = \frac{cJ}{2D\hbar} \quad \text{for "frozen" spins.}$$

This frozen spin value of the spin flip scattering rate only applies when the magnetic ion spin-spin coupling rate is small compared to the electron spin-flip scattering rate. Otherwise, some temperature dependence will occur as one moves between the "frozen" and "free" spin regimes.

If one adds this spin-flip scattering channel to the usual dephasing channel, one obtains for the critical current

$$I_c(T) = I_o \left(1-(T/T_c)^4\right) \exp\left(- L_x \sqrt{\xi_n^{-2}(T) + \xi_s^{-2}(T)}\right) .$$

While this addition improved the fits to the data, deviations remained at the lowest temperatures. We emphasize that while we allowed the parameters to vary in the course of these fits, we subsequently evaluated the resultant fit parameters subject to the constraint of physicality. We are on solid ground when we state that the above parameters are independently known either from measurement of other device properties or from the literature. For example, we measure the resistivity ρ and thus infer the electronic diffusion constant D. We furthermore know I_o through the known values for the Nb gap and device geometry, and we have confirmed this for the Nb/Cu/Nb devices (which yielded only a 25-30% reduction in I_o presumably due to proximity effects). Finally our Mn concentration is known, and the exchange coupling J is obtained from the literature.

We thus considered the presence of an additional scattering channel in our spin glass samples, since the spin glass state is not ordered in the conventional sense. We empirically added another scattering channel, assuming that it had a temperature dependent scattering rate $\tau_x^{-1} \propto T^p$ so that $\xi_x(T) \propto T^{p/2}$. Other dependences were tried, but were far less successful in fitting the data. For example, electron-phonon scattering would yield a term with p=2.

Extensive fits led to the conclusion that the data can only be adequately fit with values for the exponent p in the narrow range of 1.5 to 2. The resultant fits yielded excellent agreement to the measured temperature dependence of our devices, as well as values for the other parameters which were physically reasonable. Most convincingly, in fitting devices which only differed in their length L_x, full fits allowing *all* parameters to vary yielded consistent values for I_o, ξ_n, and ξ_s (L_x was set equal to the measured value and was not allowed to vary). Such a T^p scattering rate is indeed consistent with the temperature dependence of the low-temperature resistivity of CuMn, for which $T^{3/2}$ and T^2 behavior[2,3] have been reported.

In evaluating the physical process responsible for this extra scattering channel, we note that the inferred value for ξ_x cannot be explained by electron-phonon scattering. Electron-phonon scattering rates for Cu films with comparable resistivities are known, and are 2-3 orders of magnitude smaller than $\hbar/\tau_x$.

Since our experimental results on Nb/Cu/Nb junctions did not require the presence of an additional scattering process with a rate $\hbar/\tau_x$, the results on CuMn are strongly indicative that the process must be related to the Mn spins. Since these measurements pass through the spin glass temperature, it is perhaps surprising that no change in temperature dependence is observed as one passes through the glass freezing temperature $T_g \approx 2.5K$. Since the Mn spins in the low temperature regime are presumably frozen, it is also surprising that power law and not exponential dependence is observed. Finally, it is important to note that the scattering rate is large, which may have implications for processes involving redistribution of a large number of spins.

Hershfield has recently made the surprising observation that a simple Fermi liquid model can yield a T^2 scattering rate.[4] The physical process is an effective electron-electron scattering mediated by mediated by the magnetic ion. In this process, the first electron changes the ion spin, and the second electron comes in and re-flips the ion spin. In the process, the two electron spins are of course flipped. Simple calculation of the scattering rate by second order perturbation yields a scattering rate which is within a factor of 6 of that extracted from our fits to the temperature dependent critical currents. Furthermore, Hershfield stresses that a T^2 dependence cannot be explained by the usual spin glass excitations that have been suggested in the literature: isolated spins, spin waves, and droplet excitations.

1. Paterson, *et al.*. J. Low Temp. Phys. **35**, 371 (1979).
2. Ford and Mydosh, *Phys. Rev. B* **14**, 2057.
3. Laborde and Radhakrishna, *J. Phys. F: Met. Phys.* **3**, 1731.
4. Hershfield, *J. Phys. Cond. Mat.* **3**, 6897 (1991).

Measurement of the upper bound on the mesoscopic supercurrent fluctuations in SNS Josephson junctions

Key achievements:

- First usage of *in situ* ion bombardment of a mesoscopic device to alter its properties.
- Experimental upper bound for the mesoscopic supercurrent fluctuations of an SNS Josephson junction obtained.
- Experimental upper bound is consistent with present theoretical predictions.

In order to measure the mesoscopic fluctuations in the supercurrent of an SNS Josephson junction, one requires an ensemble of macroscopically identical junctions, that only differ in specific realization of their microscopic defects. However, there are other "undesirable" origins of sample-to-sample variations that have nothing to do with the physics of mesoscopics. Such non-mesoscopic sample-to-sample variations include deviations in the junction dimensions, the structure of and electronic transmission through the superconducting to normal metal interfaces, the superconducting properties of the S-layer electrodes, and the Nb and Cu film resistivities. Typically, geometrical differences typically dominated the critical current variations of our junctions. However, we also observed that the lithographic processing resulted in modest suppressions in the transition temperature and gap of the Nb electrodes, which varied from sample-to-sample. In the small junctions required for these experiments, such extraneous effects can easily compete with or even dominate the expected mesoscopic fluctuation. Furthermore, there is no obvious way to experimentally separate such "macroscopic" sample-to-sample variations from the desired mesoscopic variations.

We therefore decided to try a new and different approach: we would fabricate an SNS junction, measure it at low temperatures, and then *in situ* redistribute the defect distribution via bombardment with 210 keV nitrogen ions from an ion implanter. Such ion bombardment is known to produce random local defects, such as interstitial atoms. Furthermore, since the scattering cross sections are very well understood, very accurate models exist for the average number and type of defects produced as a function of dose. Our expectation was that this technique would produce a "new" sample from a mesoscopic viewpoint, yet was identical to the "old"

sample from a macroscopic viewpoint. If proven valid, such an experimental approach would have significant advantages in suppressing sample-to-sample variations that do not arise from mesoscopic effects.

We first tested this technique by sustained bombardment of Nb/Cu/Nb Josephson junctions which were fabricated using direct electron-beam lithography. Typical junction dimensions were: junction length L_x~1000Å, junction width L_y~2000Å, and normal metal thickness L_z~500Å. As the cross sectional area of the junction was $A=L_yL_z\sim10^{-10}$ cm^2, the number of electronic conduction channels $Ak_F{}^2$ was of order ~10^5. The requisite dose to produce a mesoscopically "new" sample corresponds to changing one defect for *every* conduction channel in the device. Using the industry standard TRIM computer simulation program for ion bombardment written by Dr. J.F. Ziegler at IBM, we were able to accurately calculate this requisite ion dose (which we call Φ_0) which induced the ~10^5 atomic displacements in the device. TRIM also allowed us to tailor the dose profile so that the defects were primarily induced in the Cu layer, which minimized damage-induced reduction of T_c for the Nb. The finished junctions were mounted on a dewar which was placed in the evacuated beamline of a Danfysik model 911A ion implanter. This enabled *in situ* measurements to be performed before and after ion bombardment. The sample temperature was held constant at ~4.2K to within less than 0.1mK during the course of our measurements, to avoid spurious changes due to temperature variations.

However, the *in situ* nature of this experiment had its price. In order to measure the mesoscopic fluctuation, we needed a measurement resolution of ~1 nV. While possible in a quiet noise-shielded environment, this proved exceedingly challenging in the very noisy electrical and magnetic environment of the ion implanter with its associated ion sources, 210kV electrical supplies and vacuum apparatus. Initially, variations of the critical current as large as 10% were observed, with significant noise-rounding of the device characteristics. Despite intensive efforts including multilayer electrical and magnetic shielding, separate low-noise grounding of the measurement circuitry, plus heavy electrical filtration, it was this noise which limited the ultimate sensitivity of our experiments.

Note that since the number of conduction channels in our devices was large, we are relatively insensitive to the change of a *single* defect. Hence one expects it to be difficult to observe mesoscopic supercurrent fluctuations due to individual thermally-excited atomic displacements, and our measurements in the lab bore this

out. The expected mesoscopic variation due to moving a single defect would be of order $1/\sqrt{10^5} \sim 0.3\%$ of what one would obtain for completely resetting the device.

Measurements of the variation in the average properties of our Nb/Cu/Nb junctions showed that our technique was a complete success. Upon initial ion bombardment the Cu resistivity changed rapidly, increasing by $\delta\rho/\rho \approx 35\%$ after a dose of only $\delta\Phi=5000\Phi_0$. However, with continued bombardment the resistivity increase slowed markedly. After $\sim 10^5\Phi_0$, $\delta\rho/\rho \approx 10\%$ for $\delta\Phi=10^5\Phi_0$. Thus the average change in resistivity per reconfiguration dose Φ_0 was only 1 part in 10^6! The corresponding average change in critical current per $100\Phi_0$ was determined to be ~5% of the predicted mesoscopic term. Once this average change in critical current was determined, it could then be subtracted from the data. Furthermore this slow variation only produced a reduction in the device critical current. In contrast, mesoscopic variations would be of either sign, since they average to zero in the thermodynamic limit. These results were confirmed and proven reproducible on more than a dozen junctions. The Nb/Cu/Nb junction behavior proved to be remarkably robust under the ion bombardment. The current-voltage characteristics of our junctions remained crisp with well-defined critical currents after doses in excess of $10^6\Phi_0$. The only junction failures we observed were due to dielectric breakdown of the substrate due to beam-implanted charging. This failure mode was brought under control by using electrically grounded silicon substrates which were doped to produce a conducting surface layer.

The current-voltage (I-V) characteristics for the junctions were measured after an initial dose of order $10^5\Phi_0$, which put them in the quasi-saturated dose regime. Repeated I-V measurements were taken between subsequent ion doses of $\delta\Phi=100\Phi_0$. For the most carefully studied junction, using our best noise shielding and filtration, the critical current was 1.4 mA at 4.2K. On the basis of the known device geometry and material parameters, the predicted mesoscopic contribution for a device was 500 nA or ~0.04% of I_c. The mean variation in I_c between subsequent ion bombardments was observed to be 1 ± 0.5 μA, in close accord with the theoretical predictions. Due to the presence of electrical and magnetic noise from the ion implanter, however, in the *absence* of ion irradiation we observed long-time variations in the measured I_c of 1 μA. As this is comparable to the irradiation-induced result, our results must be interpreted as providing an upper bound on the mesoscopic supercurrent fluctuation of ~1 μA. This upper bound is in good accord with both theoretical predictions by Altshuler and Beenakker.

Measurement of vortex Hall effect in single-layer and layered superconductors

Key achievements:

- Observation of the sign change of the vortex Hall effect in a low-temperature two-dimensional superconductor, with behavior qualitatively identical to that observed in high-temperature superconductors.
- Rigorous determination that the vortex Hall sign change is unrelated to the layered structure, in contradiction with recent models.

It is well known that hydrodynamic treatment of the Hall effect within the superconducting mixed state predicts a contribution due to vortex drift which has the same sign as in the normal state. However, while vortex contributions to the Hall effect are experimentally observable, recent measurements in high-T_c superconductors have found the vortex Hall effect often exhibits the *opposite* sign relative to the normal state Hall effect. Despite significant effort, the origin of this Hall sign reversal remains a controversial and vexing question which explicitly demonstrates that our understanding of vortex motion is incomplete.

While the Hall sign reversal has been widely observed in high-T_c cuprates, it is often overlooked that experiments exist upon low-T_c superconductors (LTS). LTS data exist which exhibit behavior similar to that observed in many high-T_c superconductors (HTS). Indeed, such LTS experiments show that the vortex Hall sign reversal is a common phenomenon in type-II superconductors, and therefore *not unique to HTS*. One of our contributions has been to stress this important and apparently forgotten point. In addition, HTS and LTS systems have been found where no sign change is observed. Thus, while commonly observed, the vortex Hall sign reversal is *not* a universally observed phenomenon. Furthermore, its widespread occurrence and similar behavior suggests that it has a *common* origin for both LTS and HTS materials. Furthermore, it should be clear that it does not uniquely originate from any potentially novel superconducting mechanism in the high-T_c cuprates or their unusual normal-state Hall behavior. Lastly, as we demonstrated in this study, as many models for the Hall sign reversal do not depend upon the superconducting mechanism, they are often best tested in LTS where material simplicity and/or other advantages exist.

Very recent results have appeared [J.M. Harris, N.P. Ong and Y.F. Yan, *Phys. Rev. Lett.* **71**, 1455 (1993)] upon YBCO crystals, that claim that the vortex Hall sign reversal originates from the layered nature of the high-T_c cuprate superconductors via the thermal generation of interlayer (or Josephson) vortices which exist between the superconducting layers. If true, then single-CuO_2-layer HTS films would have no vortex Hall sign reversal. However, such films are difficult to fabricate, and invariably suffer from granularity, reduced T_c, and a very high defect density.

Thus we chose to examine the sign reversal of the vortex Hall effect in model-system MoGe-Ge superconductor-insulator multilayers. Since LTS superconductors are known to display the Hall sign reversal, MoGe-Ge is an ideal testing ground due to their comparative ease in fabrication and superior material uniformity in ultrathin film form. To test the previous authors' claim, we carefully compared our results upon multilayer MoGe/Ge samples with single-layer two-dimensional superconducting MoGe films. In addition, we specifically examined the relevance of thermally-generated Josephson vortices between the layers.

We chose the MoGe/Ge system as a model system for layered superconductivity, which in many regards exhibits vortex behavior similar to HTS. For our study, the four ideal aspects of this system are: (1) the behavior of an individual layer can be independently measured; (2) their anisotropy can be controllably tuned by changing the insulating Ge-layer thickness; (3) these amorphous multilayers are free of extended defects which often plague HTS, such as grain boundaries, twin planes, intergrowths, and screw dislocations; and (4) our previous experimental studies upon MoGe/Ge multilayers with magnetic field perpendicular to the layers [D.G. Steel, W.R. White and J.M. Graybeal, "Direct Observation of Vortex Decoupling in Synthetic MoGe/Ge Multilayers", *Phys. Rev. Lett.* **71**, 161 (1993) - described later in this report] had already identified the "decoupled" vortex regime where thermal-activation of interlayer Josephson vortices is important. This decoupled regime is characterized by the absence of phase coherence perpendicular to the layers, leading to effectively decoupled 2D superconducting layers with Josephson vortices moving freely between the layers. By comparing the single film behavior with that obtained from the multilayer samples, we can separate out the contributions of the vortex motion *within* the individual 2D layers from Josephson vortex motion *between* the layers. If interlayer Josephson vortices form the sole source of the Hall sign reversal for MoGe/Ge multilayers, then a sign reversal should be absent in the single 2D MoGe film. If other contributions to the Hall sign

reversal exist within the layers, sign reversals should be observed in all samples and a measure of their relative importance can be inferred.

In fact, we found the sign reversal of the vortex Hall resistivity [ρ_{xy}] not only was present in single-layer films, but the magnitude of the reversal was actually more prominent in them. Thus, it is clear for MoGe/Ge that the existence of a layered structure is <u>*not*</u> the dominant origin of the vortex Hall sign change. Indeed, if one were to judge solely from the relative magnitudes of ρ_{xy} within the sign reversal region and interpret *all* differences as arising from Josephson vortices in the multilayers, one would naïvely infer that interlayer vortices slightly inhibit the Hall sign change. Furthermore, we found the Hall sign reversal region primarily occurs in the field-and-temperature regime below the interlayer coupling temperature $T^*(H)$. Note that the highest density of thermally excited Josephson vortices occurs above $T^*(H)$. Thus our results strongly contradict the previous claim, and any contribution to the Hall sign reversal from Josephson vortices is clearly dominated by other contributions in these samples. Should Josephson vortices remain relevant for the vortex Hall sign reversal in YBCO single crystals, it would require that a fundamentally different origin exists in other materials such as MoGe. This is of course possible. However, in view of the qualitatively similar nature of the measured $\rho_{xy}(H,T)$ for those type-II superconductors exhibiting a Hall sign reversal, it is our strongly held view that the underlying origin for this phenomenon is (1) common to HTS and LTS superconductors, and (2) that it remains unresolved.

Our results can thus be summarized as follows: while the extent of the Hall sign reversal regime did depend upon the interlayer vortex coupling, we found that Josephson vortices could *not* be the dominant contribution to the Hall sign reversal for MoGe/Ge multilayers. Hence our results explicitly contradict the earlier *Physical Review Letter*. Recent experiments on single-layer films [from Professor Chris Lobb's group at the University of Maryland] provided added support for our conclusions, and our two papers will be published in tandem in *Physical Review B*.

Direct measurement of the interlayer vortex coupling in layered superconductors

Key achievements:

- First direct observation of the interlayer coupling of vortices in a layered superconductor via electronic transport.
- First experimental observation of the theoretically predicted crossover field in a layered superconductor.
- The transport behavior for magnetic fields applied perpendicular to the layers strongly suggests the presence of *two* phase transitions, with the higher temperature transition corresponding to the direction *perpendicular* to the layers. Such observations are consistent with very recent Monte Carlo simulations.

The nature of the vortex state in layered superconductors is an important research area which enjoys considerable active interest. The statistical physics of the vortices is determined by issues such as dimensionality, thermal fluctuations, disorder and interactions. The relevant vortex interactions include magnetic and Josephson interlayer couplings, as well as vortex-vortex intralayer interactions. In light of their interplay, even the most fundamental questions persist regarding the nature of the phase diagram within the vortex state. Such critical issues include the number and character of phases involved, plus which phases exhibit true zero resistance. Considering the complexity surrounding the high temperature cuprate systems, experimental examination of model systems can provide important additional insight into these issues.

In our work, we examined the nature of the interlayer vortex coupling as a function of temperature T and applied magnetic field **H**. For sufficiently large anisotropy, the interlayer coupling energy between single-layer two-dimensional (2D) vortex "pancakes" becomes comparable to k_BT for an observable region near the mean-field phase boundary, resulting in a thermally-driven decoupled regime. Significant theoretical controversy exists regarding the expected behavior at lower temperatures, with conflicting predictions of crossover behavior and first-order phase transitions. Surprisingly, no previous experiments had directly addressed this important question. We found that this question of interlayer vortex coupling

could be simply and directly examined by sensitive electronic transport measurements in appropriately chosen experimental geometries.

While perpendicular transport is conceptually simple, it has significant qualitative and quantitative implications. We considered only the case of **H** perpendicular ($\perp$) to the layers, with applied currents either perpendicular or parallel ($||$). Unlike parallel (in-plane) transport, perpendicular transport directly probes the interlayer phase coupling. In this "Lorentz force-free" orientation, the current does not couple to rigid line vortices in linear response. We measured both the linear and nonlinear response in carefully fabricated samples.

We chose the synthetic model system, amorphous *a*-MoGe/Ge multilayers. This system has proven merits and is compatible with photolithographic techniques. In the normal state, the resistivity anisotropy perpendicular vs parallel to the layers is $\rho_{\perp N}/\rho_{||N} \cong 4\times10^4$.

As one passes through the mean field transition in the presence of an applied field, the in-plane transition is broadened, showing both fluctuation conductivity above T_c and finite resistivity below due to vortex motion. Such behavior is quite similar to that observed in YBCO. The in-plane resistivity goes to zero at temperatures well below the mean-field value. Furthermore, for a wide range of temperatures (i.e, from $T>T_c\sim5K$ down to approximately $T\sim1K$), the in-plane current-voltage response is *linear*.

The surprise is in the behavior of the perpendicular resistivity. As one passes through the mean-field phase boundary, the perpendicular resistivity $\rho_\perp$ remains *equal* to the normal-state value $\rho_{\perp N}$, showing that the layers are decoupled and the vortices are 2D in nature. No fluctuation conductivity is seen, showing that the perpendicular behavior is sensitive to interlayer phase coupling and not in-plane fluctuations. As T is lowered further below a temperature $T^*(H)$ an abrupt drop in $\rho_\perp$ is found, corresponding to the build-up of interlayer phase coupling and the establishment of line vortices. This drop is of order *six* orders of magnitude, which makes $\rho_\perp$ and $\rho_{||}$ comparable at this temperature T^*. Hence, there has been an abrupt collapse in the transport anisotropy below T^*. We add that unlike perpendicular transport in high-T_c single crystals, no substantial upturn in $\rho_\perp$ was found below T_c.

The most important observation is that substantial nonlinearities also appear in the perpendicular transport characteristics. These nonlinearities appear coincident with the collapse in the transport anisotropy, with the result that the linear response

is unobservably small. At lower temperatures and in sufficient fields, the current-voltage characteristics are power law behavior, $V \sim I^{\alpha}$, with an exponent $\alpha > 1$. Thus we observe a surprising new phase where the interlayer resistivity is vastly reduced if not equal to zero, the in-plane response is essentially unaffected, and the perpendicular current-voltage behavior has power-law characteristics. In contrast, the in-plane transport response remains linear with a finite resistance as we pass through T^*, indicating that the transition is not associated with in-plane ordering. We note that in zero-field, the I-V behavior is Josephson-like, with a well-defined critical current. Such characteristics rule out the possibility that pinhole defects between layers are dominating the transport.

In zero-field, the critical current appears to be determined by the formation of vortex loops between the layers, which are driven to the sample edges at sufficient current. Interestingly, as the field is increased from zero, the characteristics make a qualitative change on a field scale commensurate with the predicted crossover field $H_x = 2\pi\phi_0/\gamma^2 s^2$, where γ^2 is the effective mass ratio and s is the multilayer periodicity. H_x is set by the length γs, the scale on which the energy for interlayer vortex displacements crosses over from quadratic to linear dependence due to the formation of interlayer Josephson "strings". For $H < H_x$ single line vortex behavior is expected, whereas above H_x more collective behavior is anticipated. The power-law behavior we observe corresponds to the high-field regime.

In summarizing our results, we have directly observed interlayer vortex decoupling via perpendicular transport. At high temperatures, the system consists of independent decoupled 2D layers. As the temperature is reduced, interlayer phase coupling occurs at a temperature T^*. Substantial nonlinearities in the perpendicular transport simultaneously appear, suggesting the presence of a phase transition. Below T^*, we observe a precipitous collapse in the transport anisotropy, with the resistivity perpendicular to the layers becoming at most comparable to the in-plane resistivity. A crossover in behavior is also observed at a field H_x, in accordance with theory. While the full resolution of the transport nonlinearities requires further consideration, it should be clear that they impact issues critical to the nature of the low-temperature coupled state. This insight is separate from and complementary to in-plane transport results.

Recently, theoretical Monte Carlo calculations from the groups of Professor Stephen Teitel (University of Rochester) and Professor David Stroud (Ohio State University) have found identical behavior, with startling implications. They predict

that the system first goes superconducting *along the field direction* (i.e., perpendicular to the layers in our case above), with a *lower* transition temperature for current perpendicular to the field (i.e., parallel to the layers in our case)! Stroud additionally finds that the system only has a finite transition for current parallel to the layers in the presence of disorder - i.e., if the system was free of pinning, it would only superconduct along the field direction! Our experimental results are entirely consistent with the main result of their calculations, and has been specifically held up as confirmation of their results.

OFFICE OF THE UNDER SECRETARY OF DEFENSE (ACQUISITION)
DEFENSE TECHNICAL INFORMATION CENTER
CAMERON STATION
ALEXANDRIA, VIRGINIA 22304-6145

IN REPLY REFER TO DTIC-OCC

SUBJECT: Distribution Statements on Technical Documents

TO: OFFICE OF NAVAL RESEARCH
CORPORATE PROGRAMS DIVISION
ONR 353
800 NORTH QUINCY STREET
ARLINGTON, VA 22217-5660

1995 1026 099

1. Reference: DoD Directive 5230.24, Distribution Statements on Technical Documents, 18 Mar 87.

2. The Defense Technical Information Center received the enclosed report (referenced below) which is not marked in accordance with the above reference.

FINAL REPORT
N00014-91-J-1587
TITLE: MESOSCOPIC
SUPERCURRENT FLUCTUATIONS IN
SNS JOSPEHSON JUNCTIONS

3. We request the appropriate distribution statement be assigned and the report returned to DTIC within 5 working days.

4. Approved distribution statements are listed on the reverse of this letter. If you have any questions regarding these statements, call DTIC's Cataloging Branch, (703) 274-6837.

FOR THE ADMINISTRATOR:

1 Encl

GOPALAKRISHNAN NAIR
Chief, Cataloging Branch

FL-171
Jul 93

DISTRIBUTION STATEMENT A:

APPROVED FOR PUBLIC RELEASE: DISTRIBUTION IS UNLIMITED

DISTRIBUTION STATEMENT B:

DISTRIBUTION AUTHORIZED TO U.S. GOVERNMENT AGENCIES ONLY; (Indicate Reason and Date Below). OTHER REQUESTS FOR THIS DOCUMENT SHALL BE REFERRED TO (Indicate Controlling DoD Office Below).

DISTRIBUTION STATEMENT C:

DISTRIBUTION AUTHORIZED TO U.S. GOVERNMENT AGENCIES AND THEIR CONTRACTORS; (Indicate Reason and Date Below). OTHER REQUESTS FOR THIS DOCUMENT SHALL BE REFERRED TO (Indicate Controlling DoD Office Below).

DISTRIBUTION STATEMENT D:

DISTRIBUTION AUTHORIZED TO DOD AND U.S. DOD CONTRACTORS ONLY; (Indicate Reason and Date Below). OTHER REQUESTS SHALL BE REFERRED TO (Indicate Controlling DoD Office Below).

DISTRIBUTION STATEMENT E:

DISTRIBUTION AUTHORIZED TO DOD COMPONENTS ONLY; (Indicate Reason and Date Below). OTHER REQUESTS SHALL BE REFERRED TO (Indicate Controlling DoD Office Below).

DISTRIBUTION STATEMENT F:

FURTHER DISSEMINATION ONLY AS DIRECTED BY (Indicate Controlling DoD Office and Date Below) or HIGHER DOD AUTHORITY.

DISTRIBUTION STATEMENT X:

DISTRIBUTION AUTHORIZED TO U.S. GOVERNMENT AGENCIES AND PRIVATE INDIVIDUALS OR ENTERPRISES ELIGIBLE TO OBTAIN EXPORT-CONTROLLED TECHNICAL DATA IN ACCORDANCE WITH DOD DIRECTIVE 5230.25, WITHHOLDING OF UNCLASSIFIED TECHNICAL DATA FROM PUBLIC DISCLOSURE, 6 Nov 1984 (Indicate date of determination). CONTROLLING DOD OFFICE IS (Indicate Controlling DoD Office).

The cited documents has been reviewed by competent authority and the following distribution statement is hereby authorized.

A

(Statement)

OFFICE OF NAVAL RESEARCH
CORPORATE PROGRAMS DIVISION
ONR 353
800 NORTH QUINCY STREET
ARLINGTON, VA 22217-5660

(Controlling DoD Office Name)

(Reason)

(Controlling DoD Office Address, City, State, Zip)

DEBRA T. HUGHES
DEPUTY DIRECTOR
CORPORATE PROGRAMS OFFICE

(Signature & Typed Name)

(Assigning Office)

19 SEP 1995

(Date Statement Assigned)